CHAPTER 7

INSTRUMENTATION

7-1. Systematic Monitoring. Planning the monitoring program should be approached systematically. Ideally, the planning process begins with a definition of objectives and ends with actions dictated by an evaluation of the data. A hasty and unplanned approach is likely to omit consideration of many pertinent factors. The planning process should include appropriate steps as outlined below. Omission or inadequate consideration of these key planning steps will guarantee a high probability of failure and vice versa.

7-2. Proper Planning. A check list for planning will include the following steps (item 28):

a. Definition of Project Conditions. This will entail an understanding of the type, function, and duration of the structures, subsurface stratigraphy and engineering properties, ground-water conditions, status of nearby structures or other facilities, environmental conditions, construction methods, scheduling, and funding.

b. Purpose of Instrumentation. Details are discussed in paragraph 7-3.

c. Selecting Variables to Monitor. The variables selected for monitoring will depend on the project conditions and the purpose of the instrumentation. These may include water levels in the fill and stabilizing berm, pore pressure in the foundation, earth pressure in the soil mass and at the soil-structure contact, surface and subsurface horizontal deformation within the foundation, the fill, and along a sheet pile member, strain in the sheet pile, and load in anchors and tiebacks.

d. Predicting Behavior. This step helps to establish the range and accuracy or precision of the instruments. It also helps to determine where instruments should be located, Prediction of behavior also establishes a numerical value of deviation from anticipated performance at which some action must be taken to prevent failure, protect property and human life, or alter construction procedures.

e. Responsibility. It must be decided who will be responsible for procurement, calibration, installation, monitoring, and maintenance of the instrumentation system. The data must be promptly processed and evaluated by responsible individuals. It must also be decided who will react to the data and who has overall responsibility.

f. Selection of Instruments. The most desirable feature to be considered in selecting an instrument is reliability. It should be the simplest instrument that will get the job done, be durable to withstand the ambient environment, and not be very sensitive to climatic and other extraneous conditions. Other factors to be considered are cost, skills required to process the data, interference to construction, instrument calibration, special access while monitoring, accuracy, and the range of predicted responses compared with the range of the instrument.

g. Instrument Layout. A few selected critical zones should be instrumented fully; whereas, other locations may be equipped with fewer and less expensive instruments. The layout should facilitate obtaining appropriate information during each critical stage and be flexible enough such that changes can be made should there be malfunctions and as new information becomes available.

h. Preparation of Plans and Specifications. A general plan and appropriate sections and details should be developed which clearly show the locations, quantity, and installation details of each instrument. The specifications should specify who has responsibility for each activity (e.g., procurement, installation, calibration, maintenance, data collection, and evaluation) and give special instructions pertaining to each. The method of payment should be spelled out, overall responsibility designated, and authority to make changes specified. These two documents must be consistent and complete to avoid ambiguity and subsequent claims by the contractor.

i. Processing and Evaluating Data. This step includes preparing data sheets; establishing monitoring schedules; setting requirements for collecting and transmitting data; data reduction, analysis, and interpretation; and data evaluation.

j. Other Considerations. Determining factors that may influence measured data, planning to ensure reading correctness, listing specific purpose for each instrument, and acquainting new personnel with the system must be studied.

7-3. Purpose of Instrumentation.

a. The purpose of the monitoring program must be known, understood, and accepted by all pertinent parties to ensure success. Much time, energy, and money can be saved if the purpose is derived early in the process. Understanding the purpose helps to direct available resources toward specific activities, and extraneous efforts are essentially eliminated.

b. The purpose of the monitoring program may be singular or pluralistic, including one or more of the following:

(1) Verifying design assumptions and methods.

(2) Verifying contractor's compliance with the specifications.

(3) Verifying long-term satisfactory performance.

(4) Safety.

(5) Legal reasons.

(6) Advancing the state of the art.

(7) Verifying adequacy of a new construction technique.

(8) Controlling the rate of progress of construction.

(9) Accessing impact on environmental conditions.

c. The purpose will be influenced significantly by such project conditions as the type, function, and duration of the structure, the subsurface conditions, the nature and extent of the ground-water conditions, the proposed construction methods and procedures, environmental conditions, confidence in the design approach, potentials for litigation, etc. Most of this information is developed in the design stages, with new data and changes provided as the project progresses. The designer of the monitoring program should assume the responsibility of acquiring, understanding, and keeping abreast of all factors that may impact upon the monitoring program.

7-4. Types of Instruments. The kinds of instruments selected will depend on the purpose, project conditions, and the variables that will be monitored. Each variable monitored will require a specific kind of instrument, e.g., pore pressure will be monitored with some type of piezometer. A variety of instruments varying in the degree of sophistication is available from both domestic and foreign manufacturers and suppliers. The following is a brief description of the more common instruments used in a program to monitor steel sheet pile structures.

a. Observation Wells. The observation well consists of a riser pipe connected to a perforated or porous tip at the lower end and is installed in a borehole to some specified depth or attached to the sheet pile before driving. The annular space of the borehole is backfilled with sand or fine gravel and sealed at the ground surface with grout or other suitable impervious material to prevent entrance of surface water. Observation wells are mainly used to measure unconfined ground-water levels and are monitored directly by a probe or tape. If observation wells penetrate more than one aquifer or penetrate a perched water table and an underlying aquifer, the resulting water levels are average ground-water levels and are generally not very meaningful. This is a decisive disadvantage of observation wells, but if the subsurface conditions and the nature of the ground-water regime are well defined, observation wells can be installed to provide very meaningful data. Observation wells may be installed to monitor ground-water levels in the cell fill, backfill materials, and stabilizing berms. Installation can be made during sheet pile driving by attaching the casing and slotted or perforated tip (an inexpensive well point can be used) to the sheet pile. Provisions should be made to protect the tip and casing during driving if damage is likely to occur.

b. Piezometers. The term piezometer is used to denote an instrument for monitoring pore pressures in a sealed-off zone of a borehole or fill. Piezometers can be classified into five types, depending on the principle used to activate the device and transmit the data to the point of observation. The five types of piezometers include the open standpipe piezometer, the closed hydraulic piezometer, the diaphragm piezometer, the vibrating wire strain gage piezometer, and the semiconductor strain gage piezometer. A variety of each type of piezometer is available from domestic and foreign manufacturers and suppliers. Piezometers are used to monitor pore pressures in the cell fill and foundation, in the stabilizing berms, and in the backfill material. The type of piezometer selected should be based on such things as reliability, ruggedness, suitability, simplicity, cost, interference to construction, etc. The open standpipe piezometer has the advantage of simplicity and its use is widespread. In those cases where minimum time lag is a significant factor and when high artesian pressures must be monitored, a pneumatic or a vibrating wire strain-type gage piezometer would be more suitable. Installation can be made during pile driving by securely attaching the piezometer to the sheet pile and protecting the tip and riser pipe or tubes from damage. Installation after fill placement is complete can be done by any appropriate conventional method.

c. Inclinometers. Inclinometers can be used to monitor horizontal deformation within the cell fill, along the length of a sheet pile section, in the cell foundation, and within the stabilizing berm. The inclinometer system consists of a pipe installed in a vertical borehole or securely attached to the surface of a sheet pile in the cell. Normally, the lower end of the casing is anchored in rock and serves as a reference point. Casing attached to sheet pile is normally not anchored in rock. The top of the casing is referenced to monuments outside the construction area. A sensor, which measures the inclination of the casing at depths determined by the observer, is used to monitor the full length of the casing. The sensor is connected to a graduated electrical cable which is used to lower and raise the sensor in the casing. The upper end of the cable is attached to a readout device that records the inclination of the casing from the vertical. Tilt readings and depth measurements are compared with initial data to determine movements that have occurred. Plastic, aluminum, and steel casing of various sizes and shapes have been successfully used with sheet pile cellular structures. Circular casing with guide grooves and square casing are available from US manufacturers. Casing within the cell fill and in the stabilizing berm are installed in boreholes. Casing connected to sheet pile sections must be attached so that the casing remains undamaged and securely fastened to the sheet pile after the pile has been completely driven to the design depth. In-place inclinometers may be installed to provide continuous or automatic monitoring with alarm capability. In-place inclinometers can be monitored manually or automatically. The manual system consists of one or more sensors, a readout station, and a portable indicator. The automatic system consists of one or more sensors, a junction box, power supply, and data logger. For safety, the alarm option automatically generates an alarm when movement of one of the sensors exceeds a preset threshold.

d. Earth Pressure Measuring Devices. Earth pressure measuring devices fall into two categories. One is designed to measure the total stress at a point in an earth mass and the other is designed to measure the total stress or contact stress against the face of a structural element. Devices in the latter category are relatively accurate and reliable, provided the device is designed to behave similarly to the structure. In addition, the earth pressures on a structure may be reasonably uniform for the structure as a whole, but are usually very nonuniform over an area the size of a pressure cell. This condition results in a wide scatter of data that is difficult to interpret. Earth pressure measuring devices designed to measure stress at a point in a soil mass are not considered as accurate and as reliable as devices to measure stress against a structure. The main problem centers around the measuring device and the difference in the elastic properties of the surrounding backfill and the mass fill. Devices in this category are still in the development stages. A more complete discussion on earth measuring devices is presented by Sellers and Dunnicliff (item 68) and in EM 1110-2-1908. Earth pressure cells must be inspected and tested for leaks in a water bath prior to installation. The cell should be calibrated while undergoing the leak test and rechecked immediately before and after installation to ensure that the cell is still responsive to pressure change. The earth pressure cell may be installed by bonding the cell to a thin steel plate which is bolted or welded to the sheet pile member. This type of installation will cause the face of the cell to protrude beyond the face of the sheet pile. Attaching the cell such that the face of the cell is flush with the surface of the sheet pile is a more desirable installation. Measures should be taken to protect the leads and transducer from damage during driving.

e. Strain Gages. Several types of strain gages are in common use today. They may be grouped according to the principles by which they operate. Basically, three principles of operations are used: mechanical, electrical resistance, and vibrating wire. The latter two are more common in gages used to monitor sheet pile structures. Each is designed to measure very small changes in length of the structural member at the point of installation. The change in length is converted into stress, load, or bending moment. In cellular structures, strain gages have been used principally to observe interlock tension within sheet pile members. The gages are made such that they can be attached to a surface by means of an epoxy adhesive or by welding. Two types of electrical resistance strain gages are available, including the bonded types and the weldable types. Bonded types are designed to be bonded to the surface of a structural member by means of an adhesive epoxy. The success of this type of gage depends on the surface preparation of the structural members, which should be perfectly clean and dry, the gage bonding, waterproofing of the gage, which is absolutely essential, and the physical housing provided to protect the gage and lead wires. The weldable-type gages are spot welded to the structural surface with a portable welder. The resistance element is bonded or welded to a very thin stainless steel shim stock, which is spot welded to the clean smooth surface of the structural member. The success of this gage depends very much on the same factors as those affecting the success of the bonded-type gage. Vibrating wire strain gages are usually arc welded or spot welded to the surface of the structural member. Gages that are arc welded are bolted into fixed end blocks under the correct tension. The end blocks are arc welded to the structural member at the proper spacing. In gages that are spot welded to the surface, the wire is pretensioned and welded to a shim stock, and the shim stock is spot welded to the surface of the structural member. Vibrating wire strain gages are equipped with a plucking and cable assembly. This assembly is detachable with most models and can be used with more than one gage if they are in proximity. The vibrating wire strain gage operates on the principle that the natural frequency of a vibrating wire, constrained at both ends, varies with the square root of the tension in the wire. Any change in strain in the member to which the gage is attached is indicated by a change in tension in the wire. The frequency of the wire is determined by plucking the wire and measuring its frequency. Zero drift in vibrating wire strain gages, caused by stretching or creep in the wire or by slippage at the wire grips, has been reduced by heat treating the wire during manufacturing, by keeping the tension in the wire to less than 25 percent of the yield stress, and by using no load gages. Gages with thermistors for temperature measurements are available if temperature measurements are desired. Table 7-1 lists advantages, limitations, and other pertinent information for various types of strain gages used to monitor steel sheet pile structures.

f. Precise Measurement Systems. Horizontal and vertical surface displacement can be detected by making precise measurements of lengths, angles, and alignments between reference monuments and selected points on the structure. These measurements can be grouped into three categories: precise alignment measurement, precise distance and elevation measurements, and triangulation and trilateration surveys. The instruments commonly used to make these measurements include laser transmitters and receivers, precision theodolites and levels, electronic distance measurement instruments, alignment targets and reflectors, and auxiliary equipment. The reference monuments should be set in rock or stable soil, located outside the influence of the construction area, and protected from incidental disturbances. At least two reference monuments, each with a clear line-of-sight to the other and the selected points on the structure, should be installed. The selected points on the structure should be permanently marked such that the exact same points are used during each survey. In addition to the foregoing measurement systems, plumb lines can be used to measure bending, tilting, or deflections of sheet pile structures from external loading, sliding, and deformation of the foundation. A thorough discussion of precise measurement systems is given in EM 1110-2-4300.

7-5. <u>Accuracy of Required Measurements</u>. Accuracy indicates the degree of agreement between the measured value and the true value. It signifies the range the measured value will deviate from the true value. Accuracy is not to be confused with precision or sensitivity. Precision indicates the degree of agreement between repeated measurements of the same quantity and sensitivity represents the smallest quantity observable as a measurement is made. Several factors influence the accuracy of field measurements. Among these factors are the physical features of the device, installation procedures, environmental conditions, conformance of the instrument to the actual changing conditions, data reduction procedures, and observer errors. Accuracy should be verified. This can be done by monitoring two or more systems independently or by using instruments that can be removed, checked and/or recalibrated periodically, and reinstalled. The last will be virtually impossible with many instruments and

Table 7-1

Advantages and limitations of various types of surface-mounted strain gages (item 73)

Gage Type	Advantage	Limitations	Gage Length in.	Range in.	Sensitivity in./in.	System Accuracy in./in.	Reliability	Cost
Bonded electrical resistance strain gage	Small size Low cost Remote reading Can be temperature compensated	Needs great skill to install Needs great skill to waterproof Lead wire effects Cable lengths limited to 1,000 feet	0.008 to 6	±20,000	1	5 to 100	Poor to excellent	Low material; high labor
Weldable electrical resistance strain gage	Remote reading Factory waterproofing Easy installation Temperature compensation	Lead wire effects Less accurate than good bonded types	1 to 5	20,000	1	15	Good	Medium
Vibrating wire strain gage (arc welded or bolted to surface)	Remote reading Lead wire effects minimal Factory waterproofing Long history of use Robust, reusable	Small range Large size Cannot measure dynamic strain Sensitive to temperature	5 to 10	± 2,500	1	5	Very good	High
Vibrating wire strain gage (spot weldable to surface)	Remote reading Lead wire effects minimal Factory waterproofing Small size Very easy installation	Small range Cannot measure dynamic strains Sensitive to temperature Weld points need waterproofing	2 to 3	± 2,500	1	5	Good	High

installations. The required accuracy is related to several factors, including: the sensitivity of the structure to the required measurements, the magnitude of the measurements during the observational period, the length of the observational period, and the purpose of the monitoring program. These factors should be carefully considered in connection with the type of sheet pile structure being monitored and the field measurements desired. Generally, the accuracy of most readily available instruments will meet the accuracy requirements for performance evaluation of most monitoring programs, provided the instrument is installed, operated, and maintained in accordance with the manufacturer's recommendations. The accuracy of most instruments can be obtained from the manufacturer's literature. Gould and Dunnicliff (item 34), and Wilson and Mikkelson (item 95) presented tabular data on the accuracy of various measurement methods and instruments common to measuring deformation and pore pressure.

7-6. Collection, Processing, and Evaluation of Data. Data must be collected, processed, and evaluated as expeditiously as possible if the monitoring program is to have any chance of success. Careful attention must be given to whomever will collect the data. This can be the responsibility of the contractor or the owner. In any event, the person collecting the data must have experience or be trained to collect the data. This person must be aware of what constitutes abnormal data, malfunctioning monitoring equipment, and instruments that have been damaged. If the data are to be collected by the contractor, the specifications must be definite regarding who will collect the data, when and how it will be collected, transmitting the data to the owner, processing and evaluating the data, reporting malfunctions, repairing and replacing damaged equipment and instruments, and other factors unique to the monitoring program. A monitoring schedule should be established to provide data that are needed to evaluate the structure under all conditions of concern. The schedule should include special monitoring during critical load phases of the structure. Input by the design engineers will be very helpful in establishing a meaningful monitoring schedule. Initial observations should be made on all instruments immediately after installation. This is base data, and most subsequent data will be compared with this initial data. Collected data should be promptly processed for easy review and evaluation. This can be done manually or by computer technology, if computer facilities and suitable software are readily available. The choice of processing the data by computer or manually should be weighed against the volume of data to be processed, the cost of the computer systems, the personnel available, and the convenience of each method to the people evaluating the data. Regardless of the method chosen, the data should be presented in some graphic form that is readily updated as new data are acquired. Graphic presentation of data helps to establish trends, pinpoint variations, and guards against overlooking important data. Data that have been collected and processed should be promptly evaluated by design engineers and others involved in the design and construction process. The evaluation should include an assessment of the validity of the data, a determination of the existence of any adverse situation that calls for immediate attention, a correlation of the data with other activities, and a comparison of the data with predicted behavior. Care must be taken not to reject what seems to be abnormal data without due consideration of the factors likely to produce the data.

7-7. Example of Instrumentation. Figures 7-1 through 7-8 illustrate the instrumentation used to monitor the first-stage cofferdam for the replacement of Lock and Dam No. 26 on the Mississippi River. The objective of the program was to monitor the response of the cofferdam during construction and at various stages of loading and evaluate the design assumptions as well as the methods of design and analysis. The results of this program were to be used to develop recommendations for a more cost effective design of the second- and third-stage cofferdams. The intent of these figures is to provide an example of the layout and installation details of the instrumentation used in a practical situation. The details of each monitoring program must be worked out in light of the many factors unique to that program. The monitoring program for Lock and Dam No. 26 was performed under the direction of the US Army Engineer District, St. Louis, by Shannon and Wilson, Inc., St. Louis, Missouri (item 24).

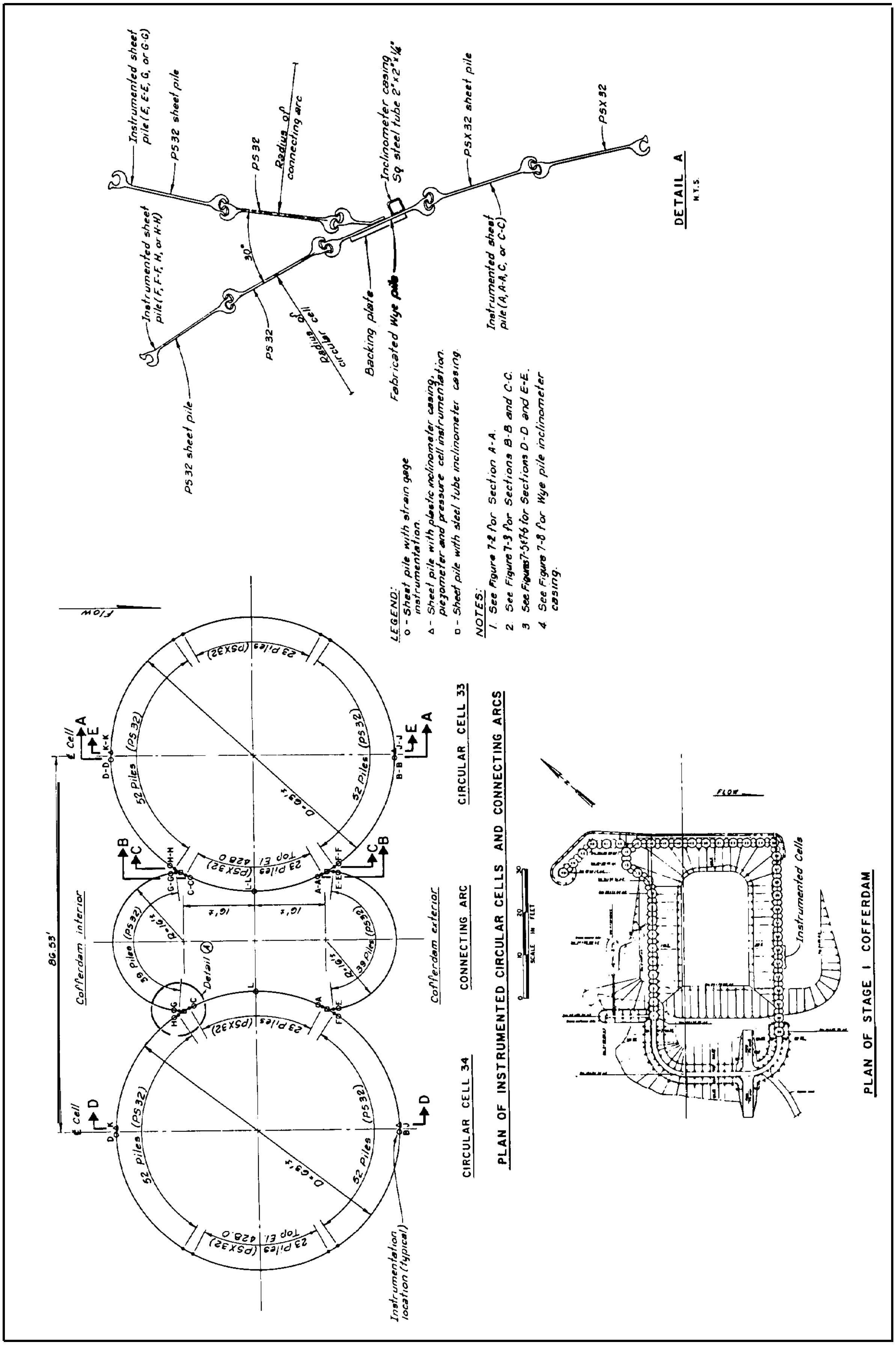

Figure 7-1. Plan of instrumentation

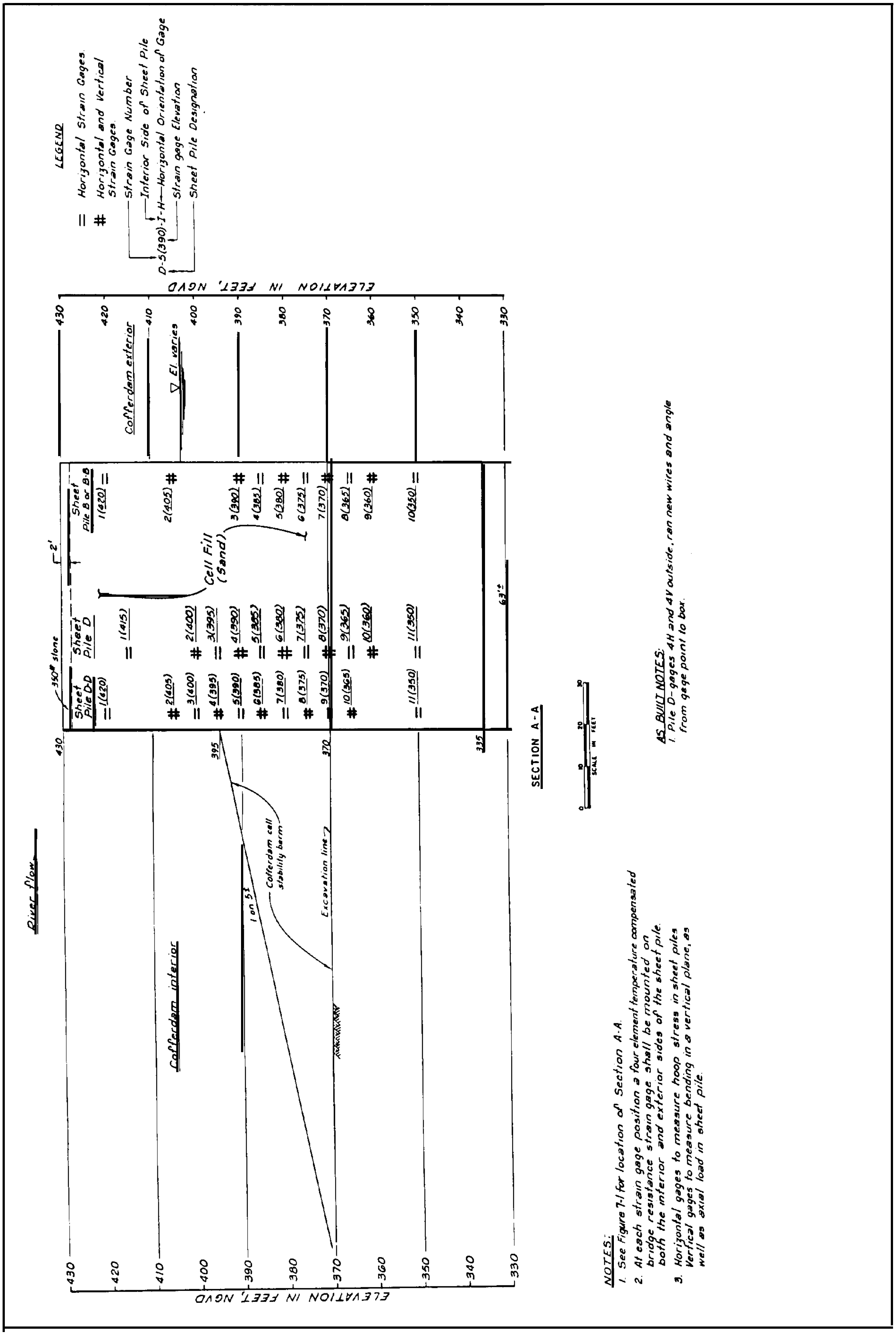

Figure 7-2. Strain gage locations

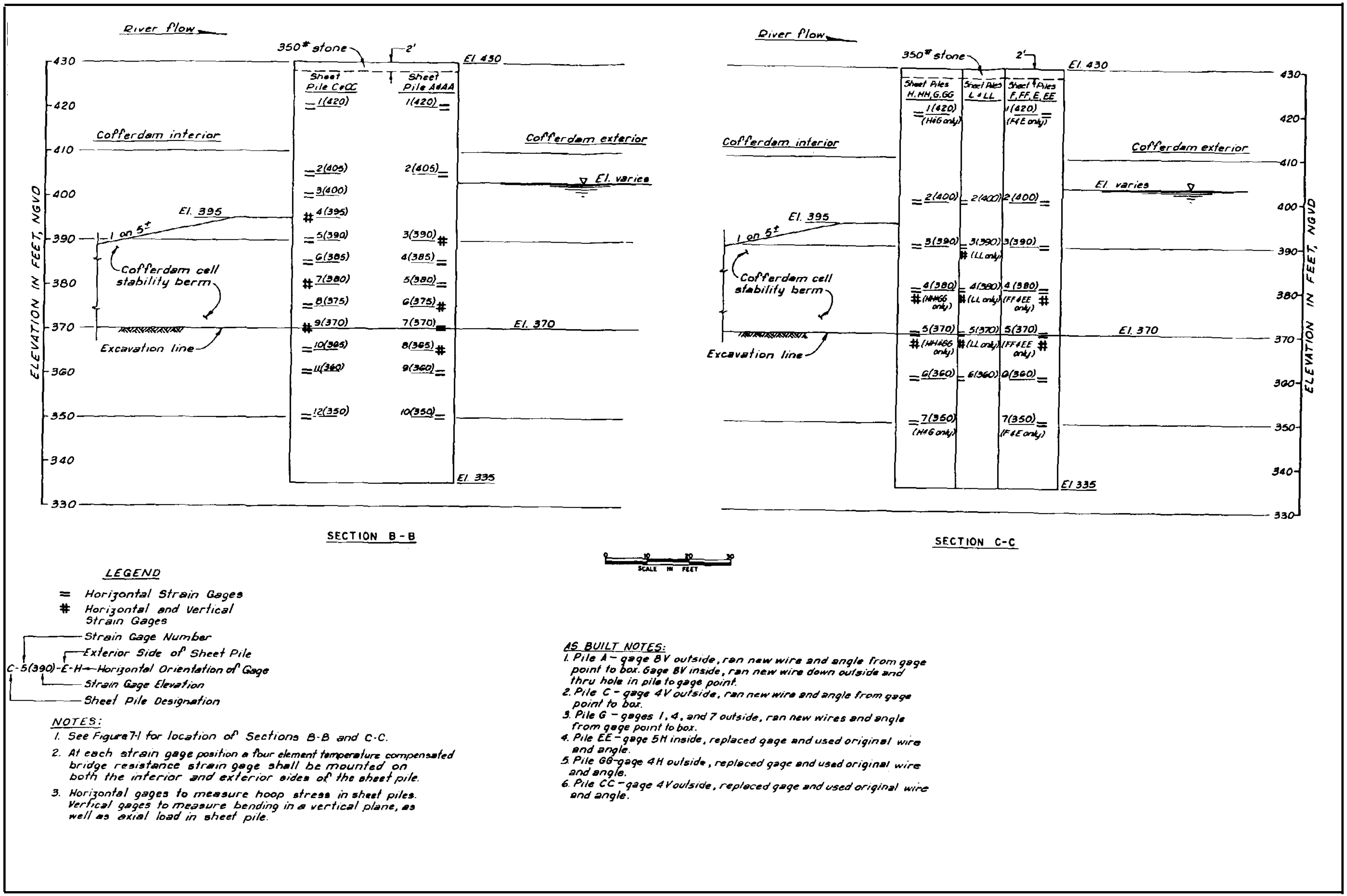

Figure 7-3. Strain gage locations adjacent to wye piles

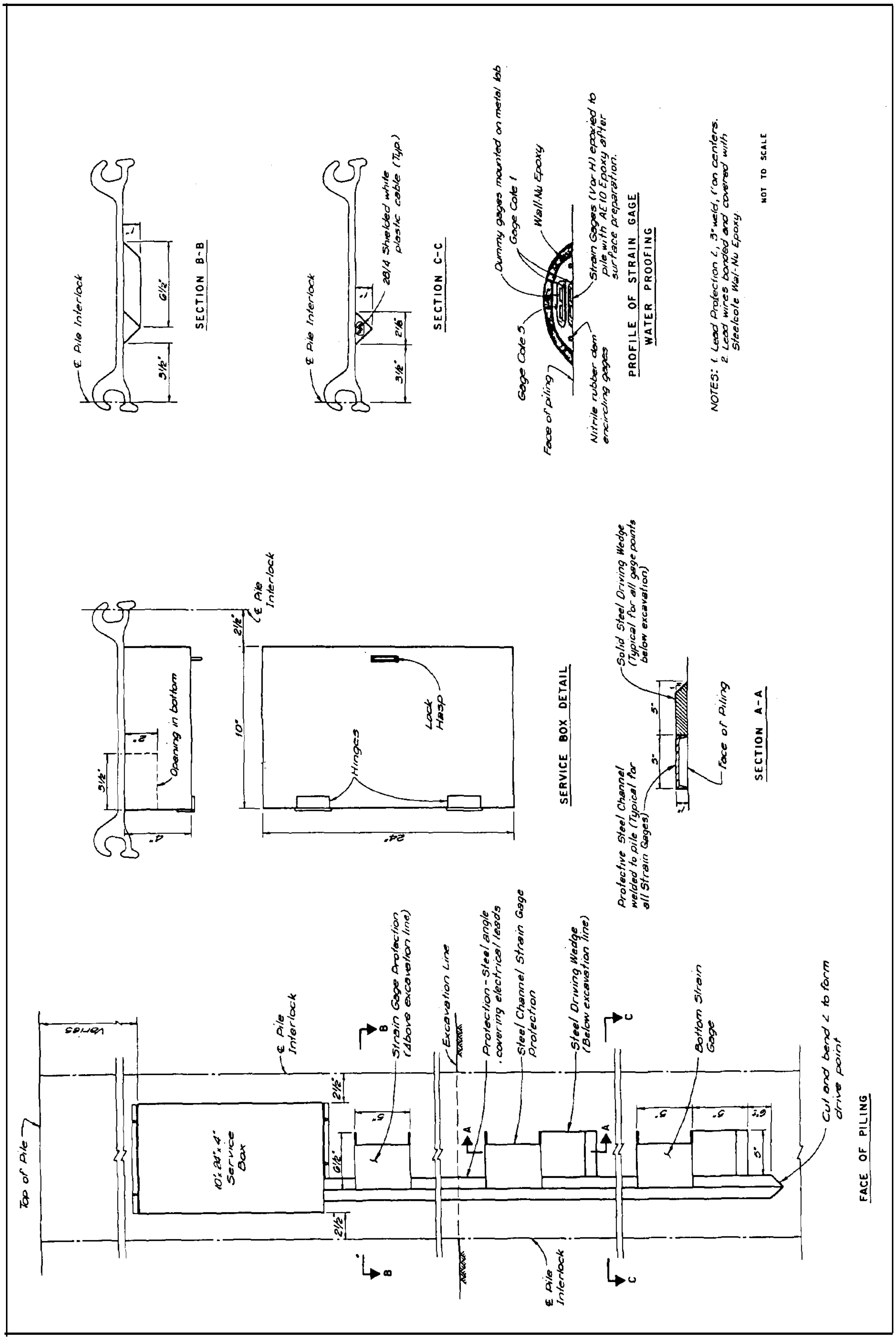

Figure 7-4. Strain gage details

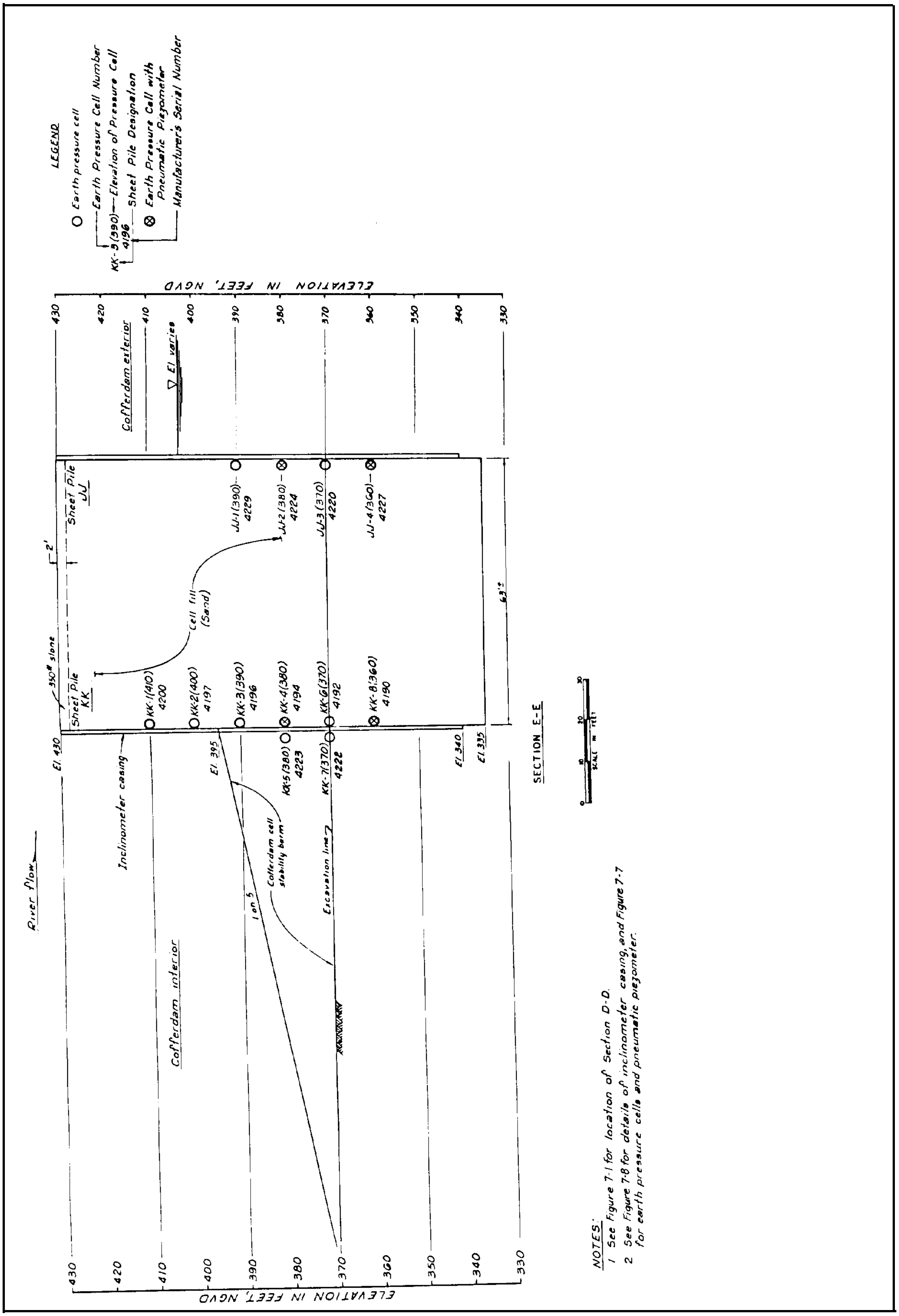

Figure 7-5. Location of earth pressure cells and inclinometers, Section D-D

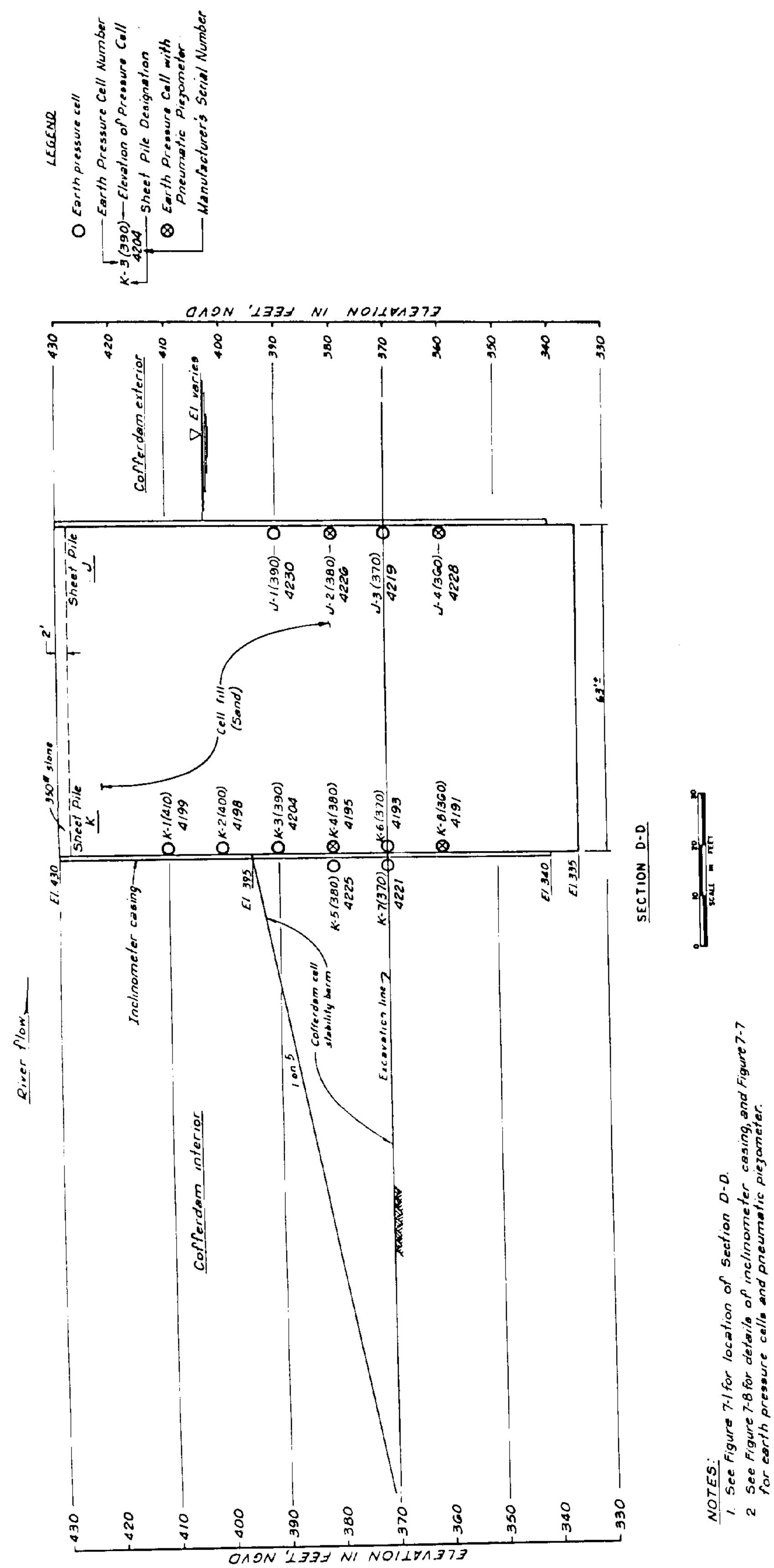

Figure 7-6. Location of earth pressure cells and inclinometers, Section D-D

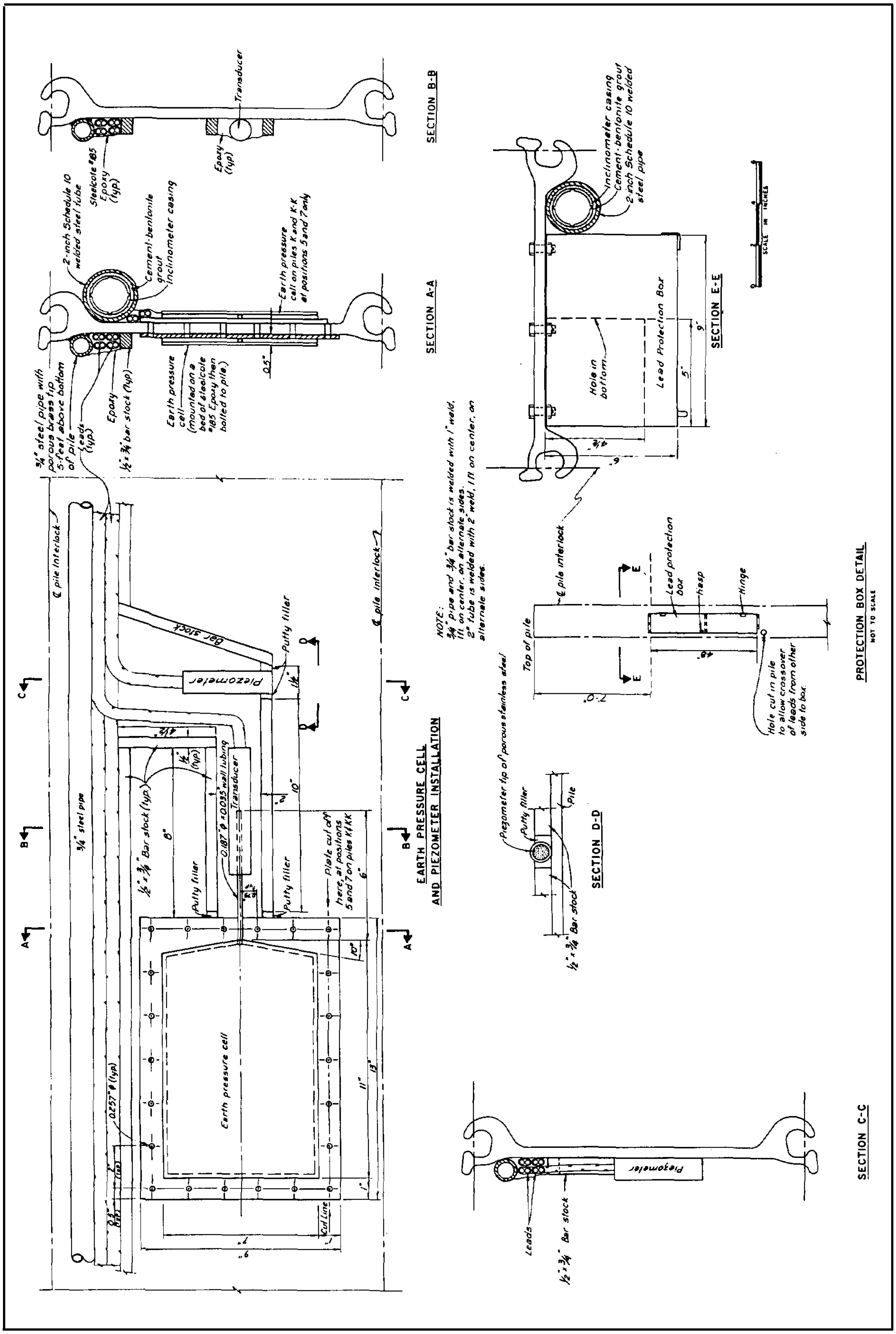

Figure 7-7. Earth pressure cell and piezometer details

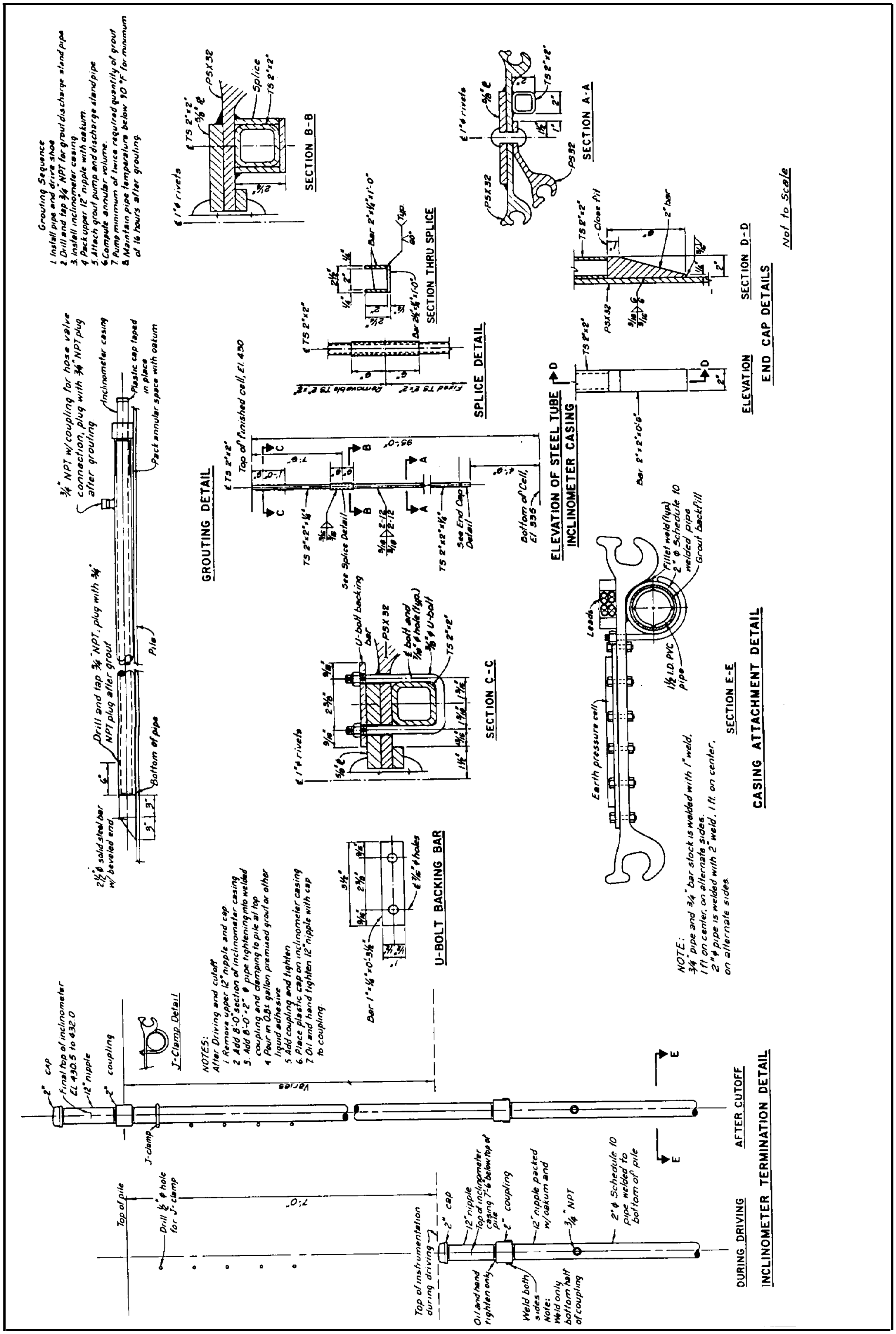

Figure 7-8. Inclinometer casing details